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## Tectono-stratigraphic architecture of the Ionian piedmont between the Arso Stream and Nicà River catchments (Calabria, Southern Italy)

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### ABSTRACT

Along the northern Ionian margin of Calabria, three Neogene basins comprise wedge-top depozones containing syntectonic deposits which cover the frontal part of the fold-thrust belt. One of the best exposed onshore allochthonous siliciclastic successions is represented by the Cariatì Nappe, cropping out in the Cirò Basin. Field geological mapping and aerial interpretations were used to characterize the stratigraphy and tectonics of the area between the Arso Stream and Nicà River catchments (about 170 km<sup>2</sup>), including a Paleozoic metamorphic basement complex unconformably overlain by Upper Oligocene to Quaternary siliciclastic deposits and minor carbonates. This paper presents a 1:25,000 scale map of the Ionian study area, providing lithological and structural data towards reconstructing its tectono-sedimentary evolution.

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### KEYWORDS

Calabrian Arc; Cirò Basin;  
Cariatì Nappe; strike-slip  
tectonics; stratigraphy

## 1. Introduction

The geology and morphological architecture of the Calabrian Arc terranes (Southern Italy) are the result of accretionary processes along its eastern flank (Ionian Sea), and rifting processes along its western flank (Tyrrhenian Margin), during the Neogene (e.g. Critelli & Le Pera, 1995, 1998; Critelli, Muto, Tripodi, & Perri, 2011, 2013; Muto & Perri, 2002; Zecchin, Praeg, Ceramicola, & Muto, 2015). The present geological setting of the northern Ionian margin is a wedge-top depozone, which is located above the thrust-sheets of the Calabrian Arc and the southern Apennine terranes (Critelli & Le Pera, 1998; Critelli, Muto, Perri, & Tripodi, 2017; Perri et al., 2012). The southern Apennine thrust and fold belt and the northern Calabrian terranes form an orogenic front, which is associated with foreland-basin systems (e.g. Critelli, 1999; DeCelles & Giles, 1996). In particular, deformed Neogene longitudinal basins (e.g. Rossano, Cirò, and Crotone Basin) represent the wedge-top depozones, into which syntectonic sedimentary cover accumulated over the frontal part of the fold-thrust belt.

The stratigraphy and structural architecture of the wedge-top basins of Ionian Calabria and the timing of deformation have been influenced by compressive structures leading to the development of distinct and asymmetric depocentres. Such on-land structures are similar to doubly verging thrusts (Critelli et al., 2011; Doglioni, Merlini, & Cantarella, 1999; Muto, Spina, Tripodi, Critelli, & Roda, 2014; Roveri, Bernasconi, Rossi, & Visentin, 1992; Van Dijk et al., 2000) documented in the Ionian

offshore and associated with the activity of NW–SE striking shear zones (Brutto et al., 2016; Knott & Turco, 1991; Muto et al., 2015; Tripodi, Muto, & Critelli, 2013; Van Dijk et al., 2000). In the study area, the strain partitioning along left-lateral strike-slip faults led to the development of transpressional features, such as the Cariatì Nappe (CN). This represents one of the best exposed onshore allochthonous siliciclastic successions of southern Italy (~1000 m thick), cropping out along the Ionian margin of the Calabrian Arc. It is thrust over the Upper Tortonian–Messinian sequences and shows an internal architecture that reflects the interplay between tectonics and relative sea-level changes. A Late Messinian–Quaternary succession unconformably overlies the CN.

A first characterization of the CN by Muto et al. (2014) analyzed the tectono-stratigraphic evolution of the allochthonous deposits of the Ionian basin, whereas the present paper draws on an in-depth geological and structural survey of the area, between the Arso Stream and Nicà River, aiming at providing more detail of the allochthonous deposits and at describing the stratigraphy of the whole succession from Paleozoic metamorphic basement to Pliocene–Pleistocene deposits. Geological units that were not formally recognized before are here described with informal names deriving from a geographic place where they typically crop out. In addition, the Neogene–Quaternary structural setting of the study area has been determined, providing information for characterizing the tectono-stratigraphic evolution of this sector of the Calabrian Arc.

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## 2. Geological setting

The study area is located along the eastern sector of northern Calabria (Southern Italy), between the Arso Stream and Nicà River catchments (Figure 1). The Calabrian Arc terranes include Paleozoic crystalline basement, thrust over ophiolite-bearing units of the Neo-Tethys domain during the Eocene. These units have covered the Mesozoic carbonate rocks of the Apenninic Maghrebide chain since the Mid-Miocene (Amodio Morelli et al., 1976; Dewey, Helman, Turco, Hutton, & Knott, 1989; Messina et al., 1994; Ogniben, 1973; Rossetti, Goffè, Moniè, Faccenna, & Vignaroli, 2004). On the Ionian side of the Calabrian terranes, the Paleozoic Alpine units and their Mesozoic cover are overlain by Neogene and Quaternary basin successions (Barone, Critelli, Dominici, & Muto, 2008; Ogniben, 1973; Roda, 1967; Zecchin et al., 2012). On the oldest units, a Serravallian to Pliocene terrigenous and carbonate sequence represents the infilling of the Calabrian foreland that can be subdivided into three main Neogene depocentres: the Rossano, Cirò and Crotone basins (Barone et al., 2008; Muto et al., 2014; 2015). The Calabrian terranes experienced a complex network of strike-slip faults and associated thrusts that strongly influenced the development of Neogene basins (Maffione, Speranza, Cascella, Longhitano, & Chiarella, 2013; Muto et al., 2014). For instance, the Cirò basin, located in an intermediate position between the Rossano and Crotone basins, lacks the Messinian evaporites (Barone et al., 2008; Muto et al., 2014). This suggests that a larger and previously continuous basin has been dissected into sub basins since the early Messinian (Barone et al., 2008; Matano, Critelli, Barone, Muto, & Di Nocera, 2014; Zecchin et al., 2013a, 2013b). The CN (Bonfiglio, 1964) represents a particularly anomalous clastic succession cropping out in the Cirò basin. It has been interpreted as an allochthonous sequence (Bonfiglio, 1964; Cotecchia, 1963) emplaced over the top of (post Messinian) terrigenous sediments (Roda, 1967). The CN represents a back-thrust, initially propagated during the late Tortonian with displacement continuing during Messinian-Pliocene time in a left-lateral NW–SE oriented transpressive fault zone (Muto et al., 2014). The basin succession of the CN is unconformably overlain by Pliocene to Upper Pleistocene succession made up of clay, sand and conglomerate, the latter forming a staircase of terraces, as observed north and south of the study area, in the Rossano (Carobene, 2003; Corbi et al., 2009; Robustelli et al., 2009a; 2009b) and Crotone (Lucà, Robustelli, Conforti, & Fabbriatore, 2011; Zecchin, Nalin, & Roda, 2004) basins, respectively.

## 3. Methods

In order to reconstruct the stratigraphic and structural setting of the study area, we carried out a detailed

geological survey of Cenozoic sedimentary deposits as well as mesostructural analysis of kinematic indicators on the fault planes and aerial-photo interpretation to characterize the structural features. In order to discriminate different deformation phases; stereoplots were developed using Daisy software.

To better illustrate the geometry of the main structures of the study area (about 170 km<sup>2</sup>), data were compiled on a 1:25,000 scale map. A Digital Elevation Model (DEM), derived from 1:5000 scale topographic maps of the Calabria Region, was used to derive a simplified topographic base with 50 m interval contour lines.

## 4. Stratigraphy

The studied succession has been subdivided into four groups: bedrock, autochthonous succession, CN succession, and Late Messinian-Pleistocene succession.

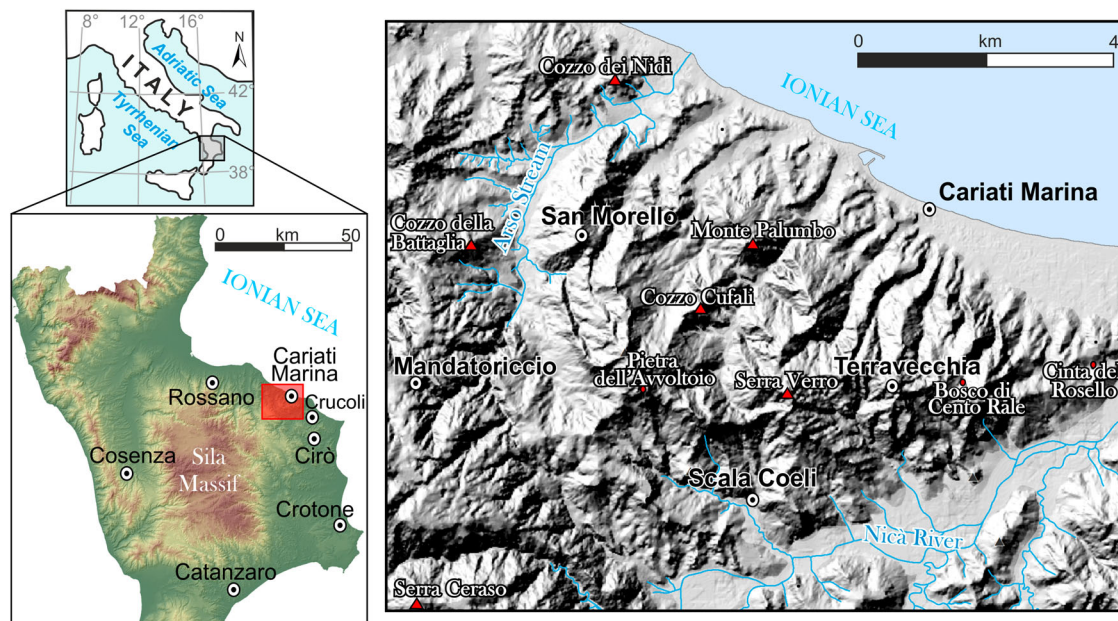
### 4.1. Bedrock

Bedrock crops out in the western sector of the study area and is represented by the Paleozoic Mandatoriccio complex (Langone et al., 2010). It consists mainly of metapelite, meta-arenite, and metavolcanic rocks with rare intercalations of marble and granitic orthogneiss. Metasedimentary rocks are locally intruded by deeply weathered granodiorite bodies (e.g. Borrelli, Critelli, Gullà, & Muto, 2015; Borrelli, Perri, Critelli, & Gullà, 2012) and, very rarely, by pegmatite and aplite sheets.

### 4.2. Autochthonous succession

Autochthonous deposits unconformably overlie the Paleozoic basement. The succession starts with the Upper Oligocene–Lower Miocene Paludi Formation (Bonardi et al., 2005), consisting of red conglomerates evolving upwards to alternating sandstones and mudstones, and cropping out to the west of Mandatoriccio. The rhythmic alternation of sandstone and mudstone records gravity-driven processes. Locally, at the base of the conglomeratic deposits, crystalline megaclasts derived from the Mandatoriccio complex occur. They are probably related to the instability of the basin margin during sedimentation.

The San Nicola Formation and the Clypeaster molasse (Serravallian–Tortonian) unconformably lie either on the Mandatoriccio complex or Paludi Formation, with a thickness of about 100 m, and represent the main substrate of Mandatoriccio village. The San Nicola Formation consists of clast-supported boulders and pebbles (Figure 2a) of an alluvial–fluvial environment, passing upwards into conglomerates and coarse-grained sandstones of the Clypeaster molasse (Figure 2b), accumulated in a shoreface environment.



**Figure 1.** Location of the study area.

The San Nicola Formation and Clypeasters molasse pass upwards into the Ponda Formation (Massari, Prosser, Capraro, Fornaciari, & Consolaro, 2010; Ogniben, 1955) which consists of 200 m thick Tortonian marly-claystone and silty sandstones interpreted to have been deposited in an offshore environment. Nearby Scala Coeli village, a lenticular sandstone deposit (Scala Coeli member) (up to 150 m in thickness) is included within marly-claystone deposits of the Ponda Formation (Critelli et al., 2014a, 2014b). Cretaceous to Eocene olistostromes made up of the so-called Varicoloured Clays occur intercalated at different levels within the Ponda Formation.

Within the Ponda Formation, located between Pietra dell'Avvoltoio and Scala Coeli, there is a lenticular diatomaceous laminite outcrop of a few meters thick comprising a sapropel-like interval of the Lower Messinian Tripoli Formation (Figure 2c). These deposits suggest that anoxic conditions due to water stratification preceded the Messinian Salinity Crisis. The contact between the Tripoli Formation and the Messinian clastic formations is only exposed near Scala Coeli and San Morello (Muto et al., 2014).

#### 4.3. CN succession

The CN succession overlies the Miocene Autochthonous succession across a tectonic contact. CN strata are characteristic of a range of depositional environments spanning fluvio-deltaic to offshore, recording two main relative sea-level rises.

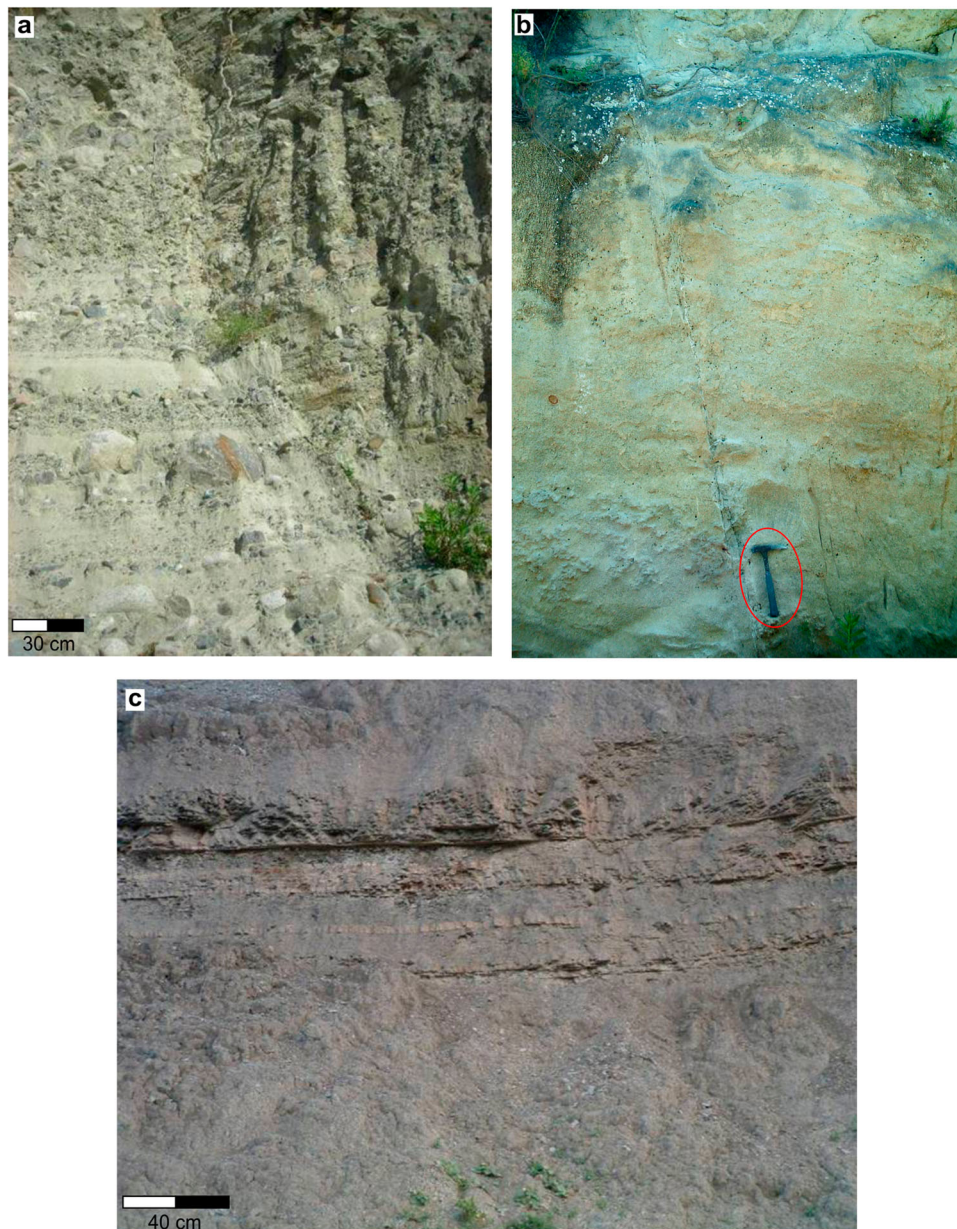
The lowermost stratigraphic unit of the CN consists of Varicoloured Clays (Cretaceous-Eocene) cropping out in the western sector of the study area, nearby Cozzo della Battaglia. The Varicoloured Clays consist of clay and shale (mainly red, blue, and green in

color) interbedded with calcilutites, calcarenites, greenish sandstones, and marls. Deposits are deformed by chaotic isoclinal folds and microfolds.

The Varicoloured Clays are unconformably overlain by the Upper Oligocene – Burdigalian Petraro Unit (Figure 3a), which is in tectonic contact with the autochthonous succession in the central part of the study area, northward of Scala Coeli town. The Petraro Unit consists of a rhythmic alternation of coarse- to medium-grained sandstones and mudstone (50–250 cm thick), interpreted to be distal turbidites. The Petraro Unit is unconformably overlaid by the Pietra dell'Avvoltoio Unit (Langhian), made up of pebble conglomerates and coarse- to fine-grained sandstones (~200 m thick, Figure 3b), accumulated in braided channel-belts, and here interpreted to be the sub-aerial distributary portion of a deltaic system. Coarse-grained deposits are encased within red mudstones interpreted as flood-plain deposits. This unit rapidly passes upward to the 250 m thick Langhian–Serravallian Monte Palumbo Unit which consists, in its lower part, of massive sandstones (Figure 3c), interpreted to be mouth bar deposits, passing upward to a rhythmic alternation of sandstone and mudstone couples up to 20 cm thick. The sandstone intervals show incomplete Bouma sequences suggesting that the unit is the result of turbidity flows.

The Serravallian–Tortonian Cozzo della Madonna Unit (Figure 3d) unconformably overlies the Monte Palumbo Unit. The 150 m in thick succession is composed of (i) clast- to matrix-supported conglomerates with well-rounded boulders and pebbles, and (ii) coarse- to medium-grained sandstones interpreted to have formed in a deltaic environment, through debris-flow processes. This unit is separated from the overlying Serravallian–Tortonian Terravecchia Unit by a





**Figure 2.** The Autochthonous succession: (a) Coarse-grained sandstone with interbedded conglomerate intervals of San Nicola Formation (Serravallian–Tortonian) and sandstone of Clypeaster Molasse (b); (c) thin stratified diatomites and cherty clay of Tripoli Formation (Lower Messinian).

gradational and heteropic contact. The Terravecchia Unit (~150 m thick) consists of coarse- to medium-grained sandstones occurring in beds of up to 50 cm thick (Figure 3e), locally including clay chips. Arenicolites, Chondrites, Skolithos, and Planolites ichnogen- era have been recognized. The unit is interpreted to be a submarine fan accumulated during low- and high- density gravity-flows.

The Terravecchia Unit passes upward to the Torton- ian Morenile Unit cropping out between the Terra- vecchia town and the Arso Stream with a thickness of 200 m. The Terravecchia Unit consists of mudstone intervals up to 200 cm thick, separated by medium- to fine-grained sandstones occurring in beds of up to 10 cm thick. Such deposits are interpreted to have been formed by low-density turbidity flows and accu- mulated in an offshore environment. The Morenile

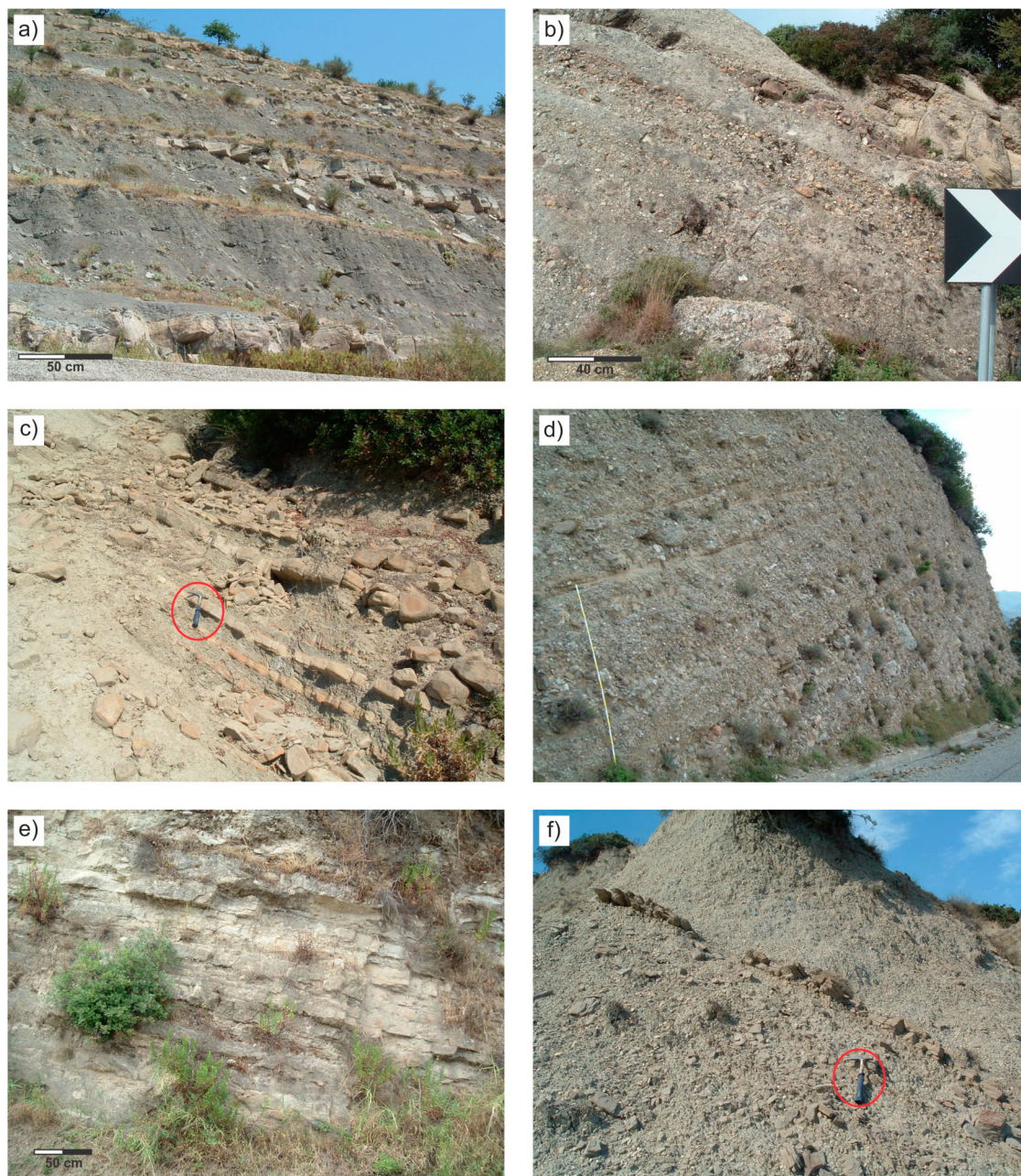
Unit crops out on the inner flank of a NW–SE syncline and is the uppermost and youngest unit of the CN. It consists of mudstone with interbedded sandstone strata (Figure 3f), here interpreted as low-density tur- bidity current deposits.

#### 4.4. Late Messinian–Pleistocene succession

The Late Messinian–Pleistocene succession lies uncon- formably on the CN. Its lower Cozzo dei Nidi Unit (Late Messinian–Lower Pliocene interpreted) crops out on the southern side of the Arso Stream. It consists of grayish fossiliferous marls and clays alternating with thin turbidite sandstone beds.

The succession passes upwards to the Cinta del Rosello mixed siliciclastic–bioclastic sandstone (Upper Pliocene–Lower Pleistocene) cropping out





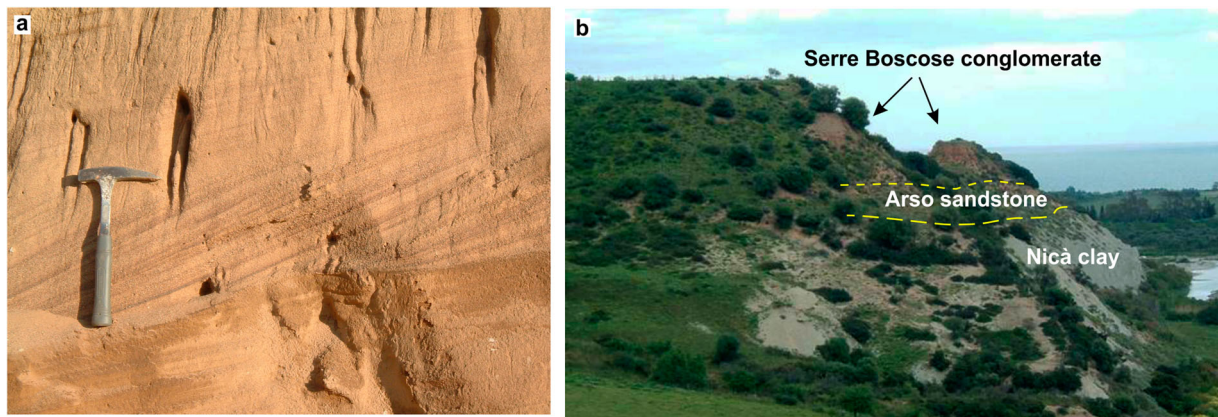
**Figure 3.** The CN succession: (a) Alternation of well stratified sandstone and mudstone of Petraro unit (Upper Oligocene – Burdigalian); (b) stratified conglomerate and coarse-grained sandstone of Pietra dell'Avvoltoio unit (Langhian); (c) alternated sandstone strata and mudstone in turbiditic facies of Monte Palumbo unit (Langhian–Serravallian); (d) stratified conglomerate with clasts and locally boulders of Cozzo della Madonna unit (Serravallian–Tortonian); (e) well stratified sandstone of Terravecchia unit (Serravallian–Tortonian); (f) mudstone with intercalation of thin arenite strata Morenile unit (Tortonian).

along the Nicà River and correlated with the Scandale sandstone formation, outcropping south of study area (Critelli et al., 2014a, 2014b). On the northwestern side of the Nicà River, the unit lies unconformably over the Petraro Unit. The Cinta del Rosello mixed sandstone is made up of unsegregated, cross-bedded siliciclastic–bioclastic sandstones (*sensu* Chiarella & Longhitano, 2012; Chiarella, Moretti, Longhitano, & Muto, 2016; Longhitano, Chiarella, & Muto, 2014) interpreted to have been deposited in shoreface and offshore-transition environments.

The overlying Lower Pleistocene Nicà clay consists of clay and gray blue marl without any apparent

stratification or sedimentary structure. This unit has been correlated with the Cutro Formation outcropping in the Crucoli Geological Sheet (Critelli et al., 2014a) and intersected by the offshore petroleum wells (ViDEPI project; [unmig.sviluppoeconomico.gov.it/videpi/](http://unmig.sviluppoeconomico.gov.it/videpi/)) drilled by Agip where it reaches 500 m in thickness. The Middle Pleistocene Arso Sandstone, correlated with the Torretta di Crucoli Syntheme occurring south of the study area (Critelli et al., 2014a), crops out parallel to the coastline and is separated from the underlying Nicà clay by an erosional unconformity. It consists of a locally stratified and bioturbated medium and coarse-grained sandstone

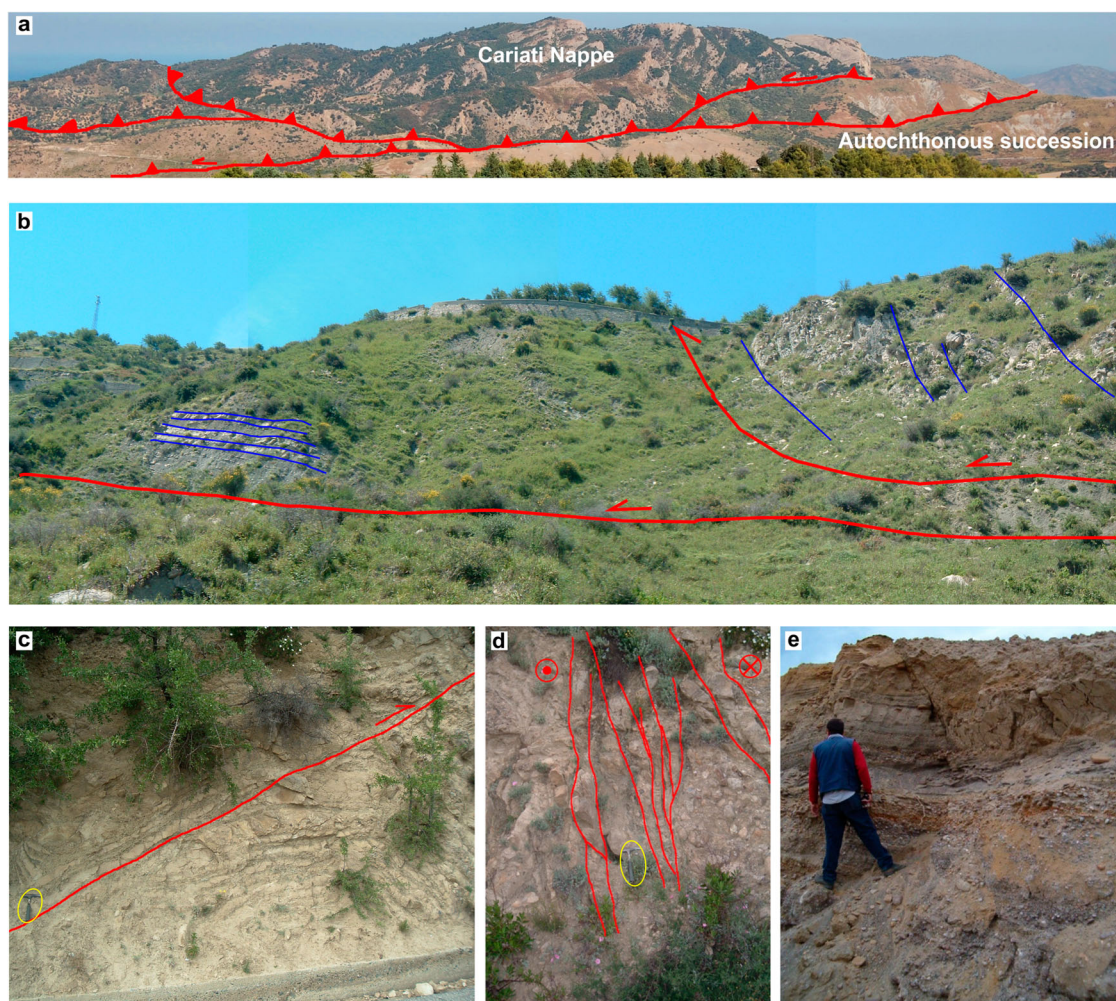




**Figure 4.** Pleistocene deposits: (a) Cross stratification in the Arso sandstone unit (Middle Pleistocene); (b) panoramic view of the Serre Boscosse conglomerate (Middle Pleistocene–Upper Pleistocene), unconformably overlying the Arso sandstone (Middle Pleistocene). At the base, the Nicà clay (Lower Pleistocene) crops out.

(Figure 4a), with a thin layer of well-rounded gravel at its base. The Middle Pleistocene–Upper Pleistocene Serre Boscosse conglomerate unconformably overlies the Mionene and Plio-Lower Pleistocene deposits (Figure 4b). It consists of subrounded, pebbles with

cobbles, sand and subordinate silt, with locally interbedded paleosols. The depositional environments include sub-aerial to submerged beaches. These deposits are arranged in a staircase of terraces the age of which has not been differentiated in the present



**Figure 5.** (a) Panoramic view the 'Cariati Nappe' from west to east; (b) thrust associated with main tectonic contact. Bedding shown with blue lines; (c) N–S and west dipping thrust associated with tight folds; (d) left-lateral strike-slip fault in the Miocene deposits. Component fault planes shown with red lines; (e) normal E–W oriented fault in the Pleistocene deposits.

study but can be correlated to the marine and alluvial terraces observed to the north, in the Rossano area (Carobene, 2003; Corbi et al., 2009; Robustelli et al., 2009a; 2009b).

## 5. Structural features

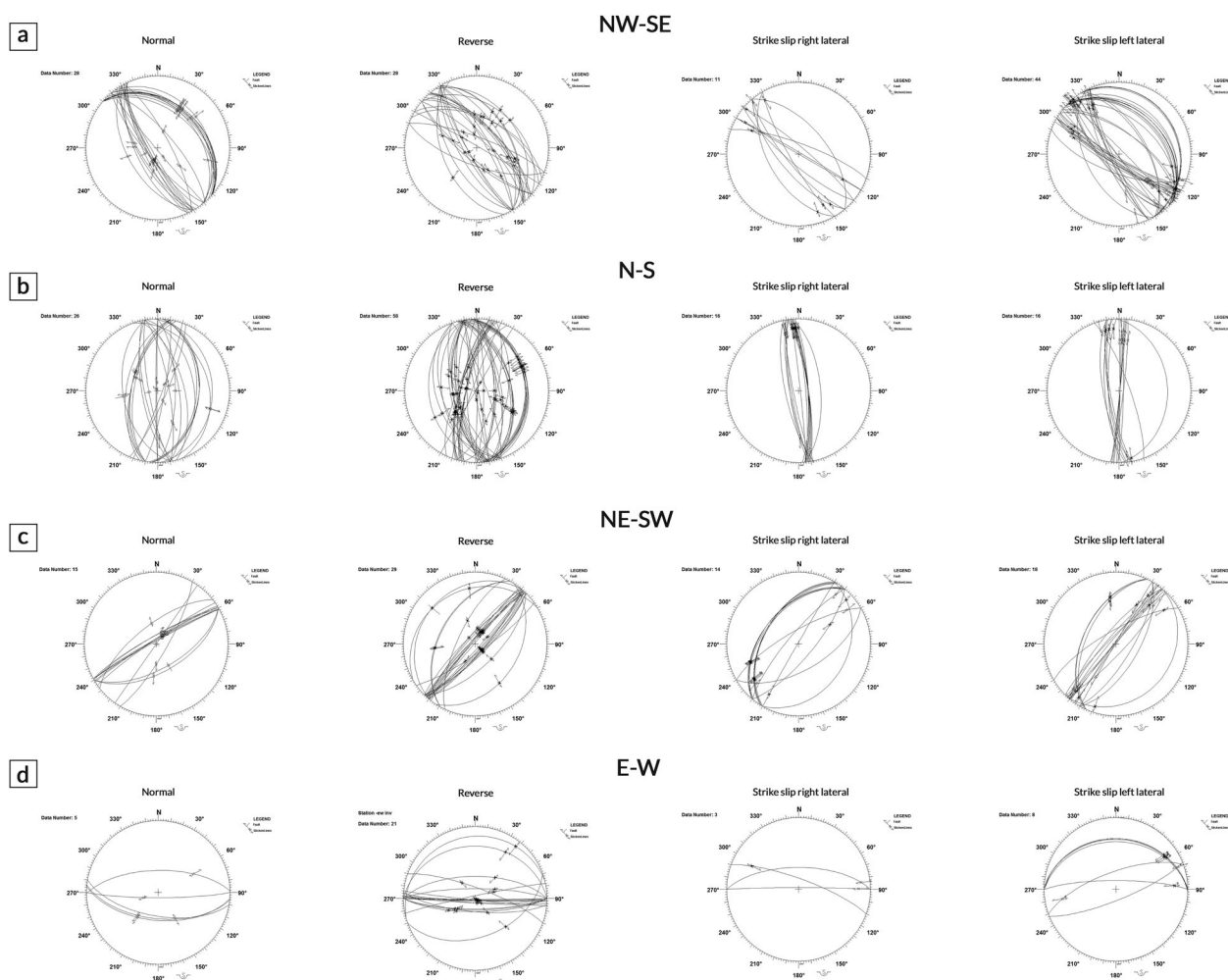
The main geological structure in the study area is a sub-vertical NW–SE striking, E dipping thrust (Figure 5a), cropping out between the Arso Stream and the Nicà River, north of Scala Coeli (Main Map). In the central sector of the study area, the tectonic contact separates the Ponda and the Tripoli formations in the footwall from the hangingwall CN succession (Figure 5a). In the northwestern part of the study area, on the north side of the Arso Stream, the thrust is underlain by footwall Cozzo dei Nidi sandstone of late Messinian to lower Pliocene age (see Main Map).

Within the CN succession, the west verging anticlines and synclines, with generally eastward dipping strata are related to the main thrust and to the splay ramps (Figure 5b). The fold axes are mainly NW–SE oriented; subordinate N–S trends also occur

(Figure 5c). Similarly oriented mesoscopic folds have been widely observed near Terravecchia.

The main anticline located north of Petraro, has a NNW–SSE oriented axis and plunges toward the NNW. The Petraro Unit crops out in the core of the fold whereas the outer limbs are characterized by the remaining successions of the CN. Near Bosco di Cento Rale, a NW–SE oriented syncline with the Moronile Unit exposed in the core has been mapped. Fold axes in the area are curvilinear.

The faults surveyed in the study area are mainly NW–SE trending with strike-slip (left and right lateral), reverse and normal kinematics (Figure 6). The distribution of fault kinematics has been distinguished according to trends and ages of displaced stratigraphic units. The NW–SE fault planes are widespread at the contact between the Autochthonous and the CN successions and between the substrate and the autochthonous Middle Miocene deposits (see Main Map). These structures are most frequently strike-slip with a reverse-slip component (i.e. oblique-slip) and dip-slip reverse faults (Figure 6a). Along the main contact and at the mesoscopic scale these faults exhibit typical transpressive geometry. They are left-lateral dominant



**Figure 6.** Schmidt net (lower hemisphere projection) of faults collected in the study area; data are subdivided according to strikes and kinematics.



(Figure 5d) with a high angle of inclination and dipping towards the NE. Pleistocene deposits have been dissected by E–W striking, high angle normal faults with a component of right-lateral displacement (Figure 6d), which also displace the staircase of terraces (Figure 5e).

Geological mapping revealed the occurrence of polyphase deformation. In fact, within the CN succession and mainly at the hangingwall of the main thrust, N to NE trending splay thrusts accommodate strike-slip deformation (Figures 5c and 6b, c) in addition to fold axes showing evidence of re-folding at both large and mesoscopic scale (Figure 5c).

Moreover, the dip of Pliocene–Pleistocene deposits decreases up-section due to synsedimentary growth of a monocline fold limb (Barone et al., 2008; Muto et al., 2014), accompanied by progressive unconformities observed in the Pliocene–Quaternary basin-fill succession (see the Main Map and geological cross section).

These observations of kinematic chronology on the NW–SE fault planes, dip-slip reverse kinematics followed by strike-slip kinematics, support the hypothesis that after the initial frontal thrust propagation of the CN succession (Muto et al., 2014), the tectonic regime changed from compressive to strike-slip, allowing progressive northward migration of the new transpressive thrusts, involving younger deposits. In addition, the reactivation of older fault planes showing variable displacements, from dip-slip to oblique-slip with normal kinematics in the autochthonous and CN successions, coupled with the occurrence of more recent structures in the Pliocene–Pleistocene succession, indicate a phase of transtensional reactivation during the Quaternary.

## 6. Conclusion

Sedimentological and structural mapping has revealed in more detail the tectono-stratigraphic setting of the area between the Arso stream and the Nicà river catchments along the northeastern margin of the Calabrian Arc, where allochthonous terranes of the CN were emplaced over the Neogene stratigraphy of Crotona and Rossano basins.

Geological survey data provide tectono-sedimentary and structural constraints for the tectonic emplacement of the allochthonous terranes. Structural analysis reveals transpressional features resulting from strain partitioning along left-lateral-slip faults. In particular, the CN is the result of compressive/transpressive tectonic phases from late Tortonian to Pliocene (Muto et al., 2014) or to Pleistocene (Ferranti, Santoro, Mazzella, Monaco, & Morelli, 2009; Gori, Falcucci, Fubelli, Muto, & Dramis, 2016) leading to the formation of a composite NW–SE and N–S oriented back-thrust. Similar thrust geometries have been documented in the Ionian offshore of the northern

Calabrian margin by Ferranti et al. (2009) consisting of an array of transpressional faults considered to be tectonically active (Gori et al., 2016). Structural analyses at outcrop and mesoscopic scale show that the upper Miocene back-thrust migrated progressively northwards from the Upper Tortonian. During the Messinian–Pleistocene allochthonous terranes were reworked by left-lateral NW–SE oriented transpressive fault zones that thrust the CN over the autochthonous succession marking the oblique component of collision between the southern Apennines–Calabrian Arc system and the Apulian block.

## Software

The cartographic operations of geo-referencing, digitization and editing of the geological field data, as well as the related layout, were carried out using the Esri ArcView 3.2. The stratigraphic column, cross section and arrangement of figures were developed using Corel Draw Graphic Suite X6. Daisy software was used for the stereoplot representation of mapped faults.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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